THE LaRC CSI PHASE-0 EVOLUTIONARY MODEL TESTBED-DESIGN AND EXPERIMENTAL RESULTS

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Abstract

A testbed for the development of Controls-Structures Interaction (CSI) technology is described. The design philosophy, capabilities and early experimental results are presented to introduce the reader to some of the ongoing CSI research at the NASA Langley Research Center. The testbed, referred to as the Phase-0 version of the CSI Evolutionary model (CEM), is the first stage of model complexity designed to show the benefits of CSI technology and to identify weaknesses in current capabilities. Early closed-loop test results have shown non-model based controllers can provide an order of magnitude increase in damping in the first few flexible vibration modes. Model-based controllers for higher performance will need to be robust to model uncertainty as verified by System ID tests. Data are presented that show finite element model predictions of frequency differ from those obtained from tests. Within the paper, the hardware implementation of CSI systems is emphasized. Plans are also presented for evolution of the CEM to study integrated controller and structure design as well as multiple-payload dynamics.

Introduction

The focused research being performed for the development of CSI technology consists of three complimentary stages: design, ground testing and flight testing. Within each of these stages, further divisions can be made, e.g. micro-precision disturbance rejection, global line-of sight pointing control, multiple-payload isolation, multi-body robotic control, etc. Hence, it is important to establish the CSI technology to be addressed by the testbed described herein.

The CSI Evolutionary Model (CEM) is first and foremost a ground based testbed for validation of design methodology and hardware implementation. As such, the CEM has been designed to permit numerous hardware changes. There are three planned phases for the evolution of the hardware. Phases 0 and 1 are both linear time invariant systems, however, the design philosophy are different. Phase-0 is based on a classic design of uniform strut size in the truss, nominal placement of actuators and sensors and subsequent controller design based on the fixed plant. Phase-1 will be fabricated based on an integrated controller and structure design whereby both structure and controller design variables are sized simultaneously. Performance and stability comparisons between Phase-0 (uniform truss stiffness and mass) and Phase-1 (tailored truss stiffness and mass) will be made to establish the benefits of integrated design. Phase-2 will permit appendage articulation for the study of time variant dynamics typical of Multiple Payload Platforms (MPP).

There are two major CSI technologies being addressed by the Langley Research Center using the CEM. In Phases 0 and 1, global Line-of-Sight (LOS) pointing is the primary objective. In Phase-2, MPP will be studied to develop multiple-payload isolation technology. For additional NASA related CSI research, the reader is referred to the Jet Propulsion Laboratory (JPL) for CSI technology developments aimed at optical systems which require micro-precision control and to the Marshall Space Flight Center for the development of CSI flight experiments. In addition, both Langley and JPL are developing analysis and design tools for CSI systems.

The remainder of this paper will focus on the design and early experimental results of the Phase-0 version of the CEM. Future plans for CEM based focused research are also presented.

CSI Evolutionary Model

The CEM has been designed to posses dynamic properties typical of spacecraft platforms proposed for remote sensing and communications. As shown in the schematic below, the Phase-0 version of the CEM consists of a long truss bus and several appendages with varying degrees of flexibility. To monitor the LOS pointing accuracy, a low powered laser has been mounted on the vertical tower such that the beam reflects upon a mirrored surface mounted on the reflector. The beam reflection is measured by a photo-diode array attached directly above the reflector. This laser-reflector-detector system enables the pointing accuracy of the CEM to be measured to a tolerance of 500 micro-radians when the photo-diode array is mounted on the laboratory ceiling (700 inches above the reflector). The CEM is suspended by two cables attached to the laboratory ceiling. By using springs in series with the cables, all 6 "rigid"body modes have a frequency below 1 Hz. The first flexible body frequency is at 1.5 Hz with a total of 31 modes below 10 Hz. The following pages describe the hardware in more detail.
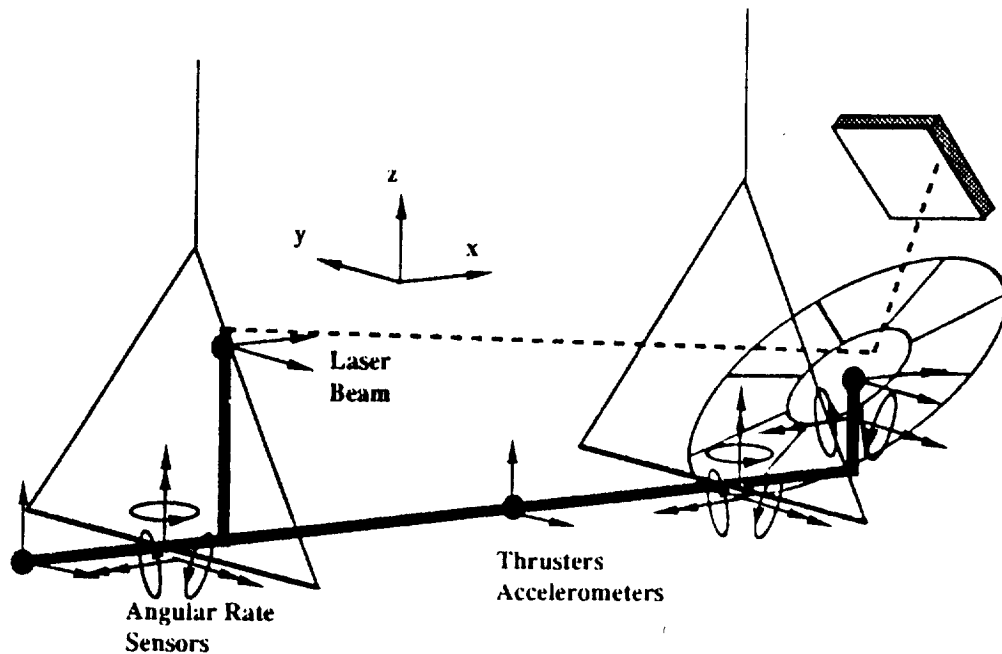
CEM Structural Hardware

The design of the CEM was driven by several conflicting criteria. A large model was desired such that actuators would need to be sized for large inertia properties typical of space platforms. The model was to be ground tested, hence, the design of the suspension system and truss strength must withstand gravity preload. Moreover, while a strong truss was desired to permit significant dynamic member loads during controls testing, only moderate truss stiffness was desired to enable visual indication of the effects of flexible body dynamics. These criteria were used to select a truss structure with a 10 inch cubical bay. The truss tubes are aluminum with special end fittings to permit assembly using node-ball joints. For analysis purposes, an effective area of the truss members has been used to model the stiffness from node-center to node-center as: longerons and battens = 0.12316 in^2 , diagonals = 0.1166 in^2. There are 62 bays along the main bus, 11 bays on the laser tower, 4 bays on the reflector tower and four horizontal 10 bay appendages to which the suspension cables are attached. The reflector has eight 0.25 inch thick aluminum ribs which taper in width from 2 inches to 1 inch over their 96 inch length. One end of the ribs attach to a hub, which is affixed to the truss reflector tower, while the other end of the ribs are connected to each other by a pretensioned cable. A honeycomb panel with a mirrored surface is affixed to the ribs and to the hub.
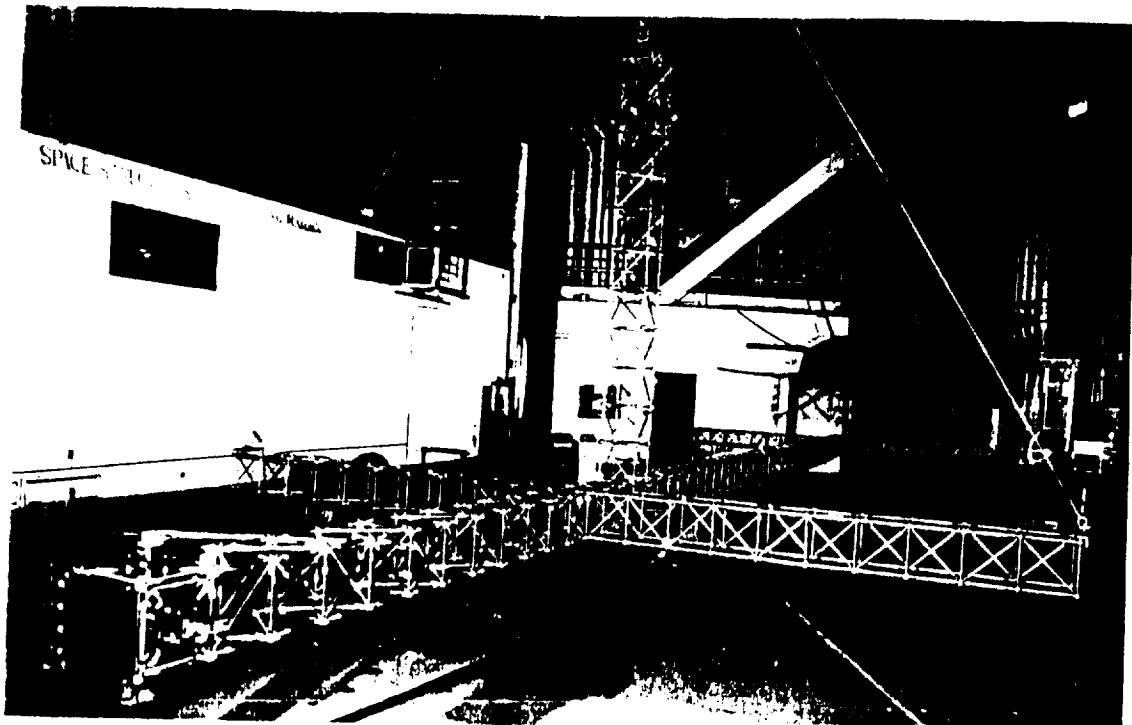
Typical CEM Vibration Modes

The cable suspended CEM has six "rigid" body modes of vibration. Three of the modes occur near 0.15 Hz and involve horizontal translation and rotation in the X-Y plane. Two modes occur at 0.72 and 0.74 Hz and involve vertical bouncing in the X-Z plane. The sixth "rigid" mode involves compound pendulum dynamics in the Y-Z plane at a frequency of 0.90 Hz. The first three flexible body modes of vibration, shown below with the FEM predicted frequency, involve bending and torsion of the CEM. Analysis models predict 81 modes of vibration below 50 Hz.

Mode 7   1.435 Hz
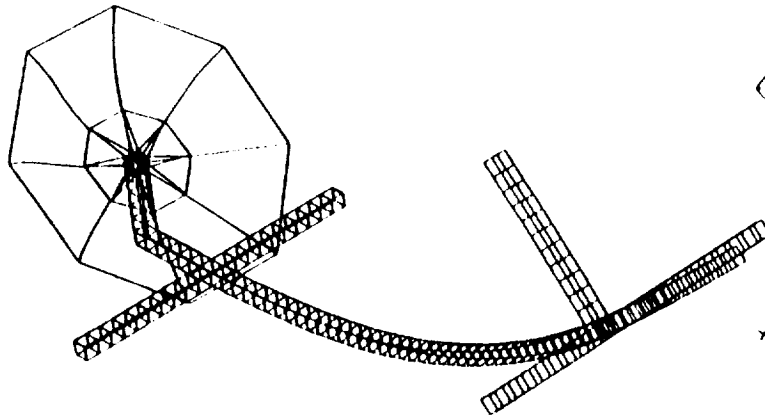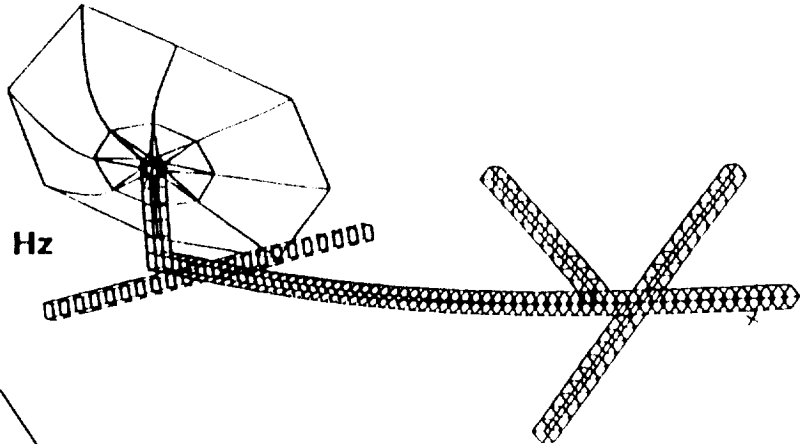
**Mode 8 1.680 Hz**

Mode 9 1.833 Hz

5
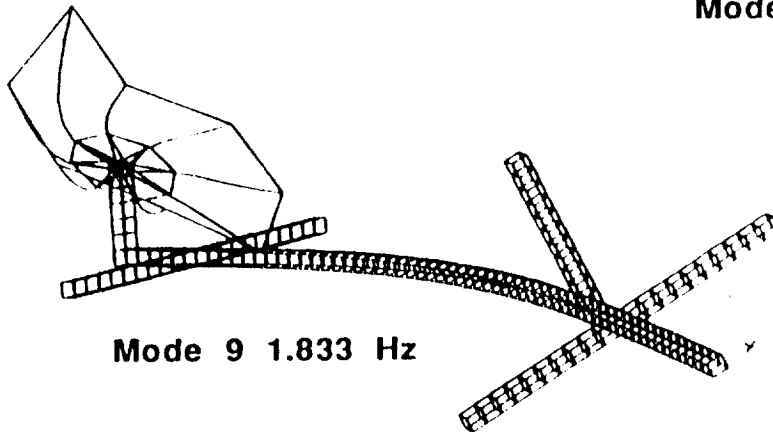
CEM Actuation Devices

Compressed air thrusters [1] are the primary control actuators on the CEM. The 16 thrusters are proportional bi-directional force actuators and produce up to 2.2 lbs of force. A local controller is implemented for each thruster to linearize the input/output response. As shown below, the thruster dynamics is easily described by the first order model

$$\frac{force}{volt} = \frac{55.439}{(s+273.05)}$$

where s is the Laplace variable. This model, developed from aggregate bench tests of the thrusters, indicates 1 db magnitude attenuation and 12 degrees of phase lag at 10 Hz. The thrusters have been installed in four groups on the CEM. Each group has four thrusters acting in pairs to achieve pure translational forces.

In addition to the air thrusters, proof mass, piezo-electric, piezo-ceramic, and visco-elastic actuation devices are planned for implementation during the CEM test period.


Pneumatic Actuator

6
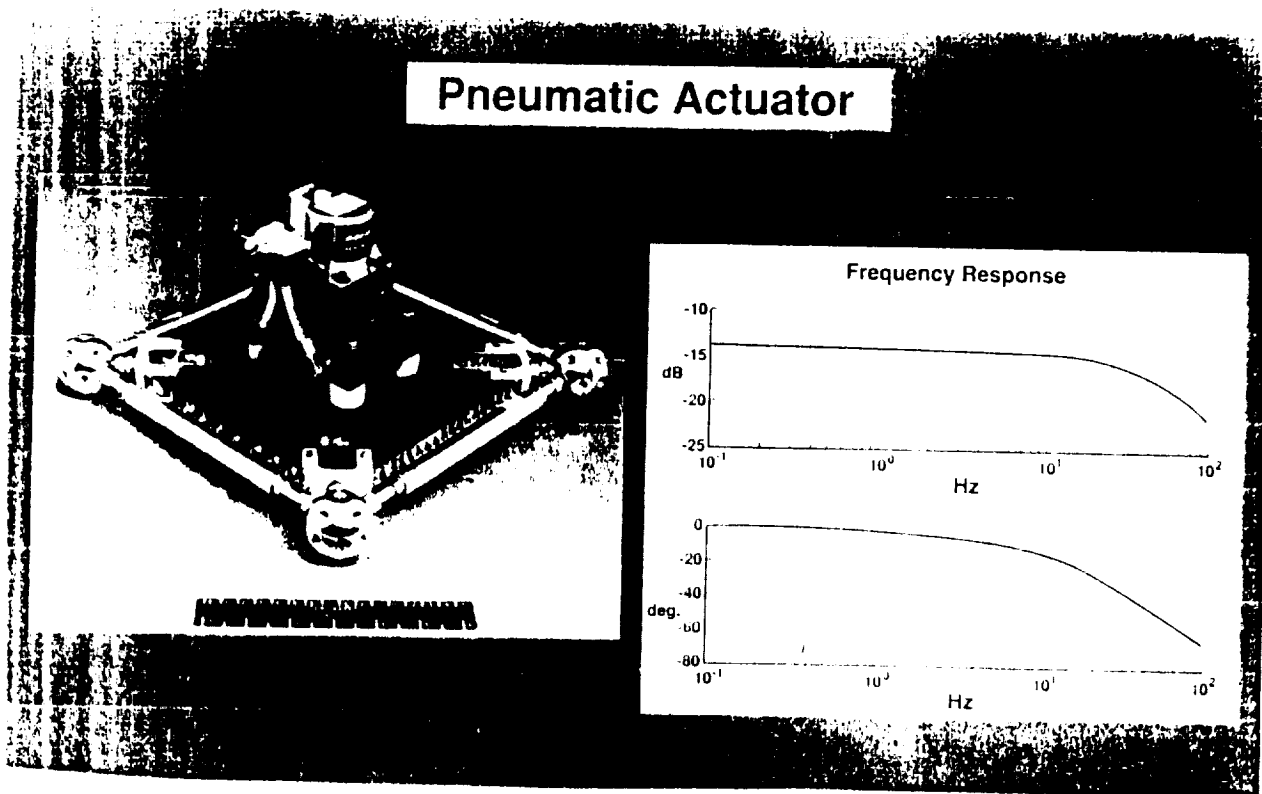
CEM   Sensors and Filters

Currently, there exist two classes of sensors on the CEM; control sensors and system ID sensors. For control, servo accelerometers with 5 volts/g sensitivity and angular rate sensors with 3-10 volts/(radian/second) sensitivity are used. For ID, piezo film accelerometers with 1 volt/g sensitivities are used. There are a total of 28 servo accelerometers, 8 angular rate sensors and 195 piezo film accelerometers on the CEM. Sensor dynamics for the servo accelerometers (primary control sensors) can be virtually ignored up to a bandwidth of 300 Hz unless the sensor data is pre-processed by available analog filters. Three pole Bessel filters with 10, 20, 50 and 100 Hz cut off frequencies are available to pre-process the data. Typical sensor mountings on the CEM are shown below.
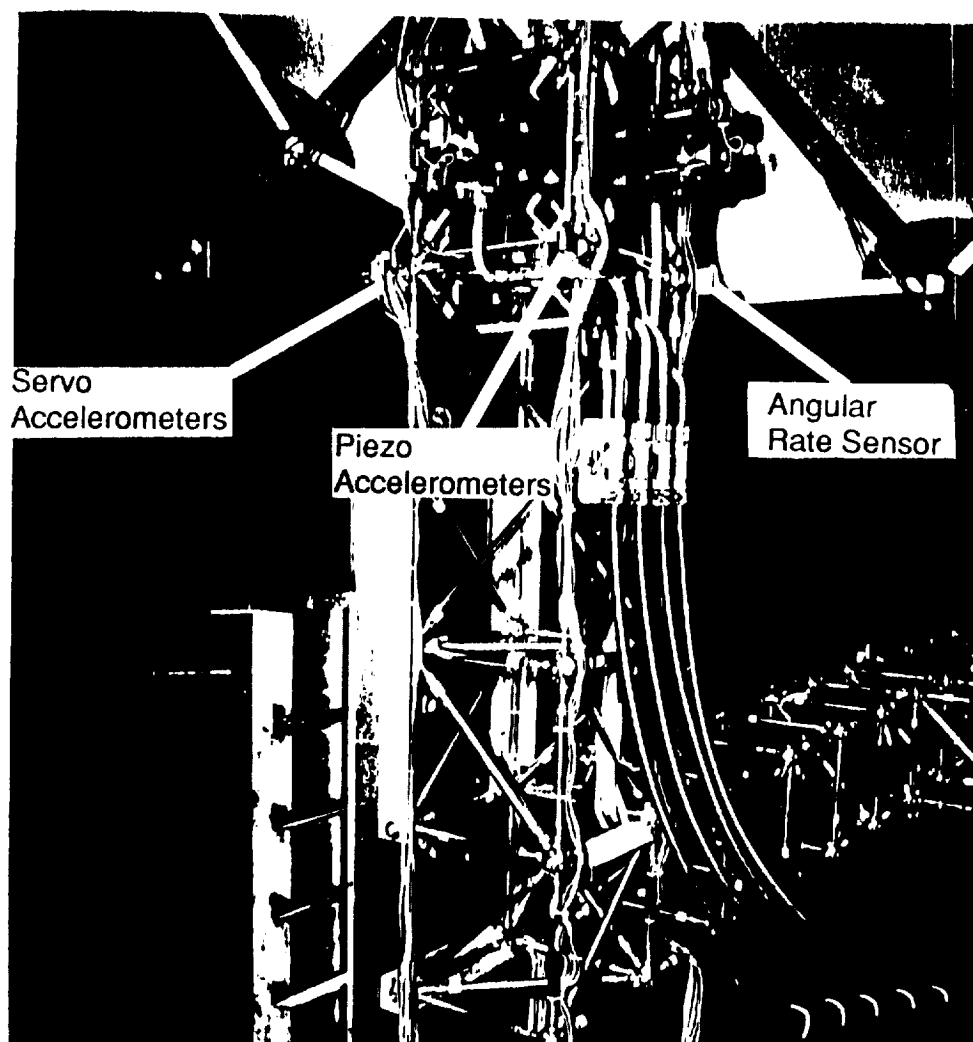
CEM Real-Time Digital Computers

There are three non-pc based computers used for real time computing. As shown below, a VAX 3200 and a CYBER 175 [2] are interfaced to a CAMAC crate which provides a digital interface to a number of bus protocols. In addition to these computers, a SCI flight equivalent computer will be interfaced to the CEM via a Remote Interface Unit (RIU) which provides local digital processing, A/D and D/A conversion and interfaces to the SCI computer over a 1553 digital bus. Each of these computers is capable of performing real time computations although the control updates rates have not been fully tested. Typical controllers (16 states, 8 input and 8 output signals) have been executed at a rate exceeding 150Hz. using the CYBER and VAX computers. The Cyber computer is part of Langley's Advanced Real-Time Simulation (ARTS) system. The CYBER is currently being upgraded to a 4 processor CONVEX computer which should permit considerably faster controller update rates. The SCI computer update rates are not yet tested.

8
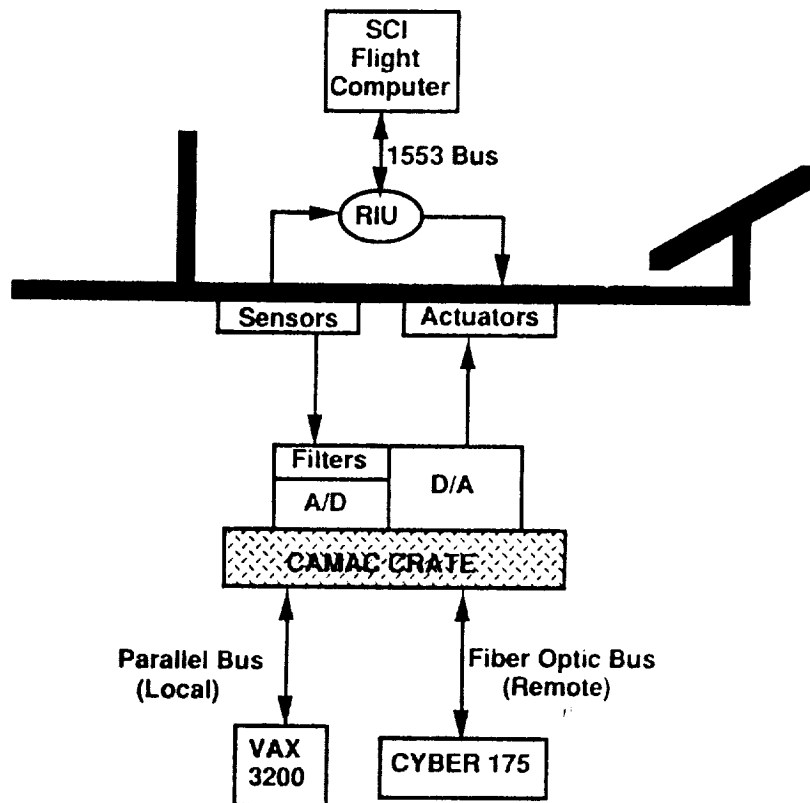
Line-Of-Sight Pointing Control

For the Phase-0 CEM, the LOS pointing accuracy is the performance measure of primary interest. Simulation studies [3] have shown that the amount of energy used to control LOS pointing varies greatly for different controllers. As the charts indicate below, Linear Quadratic Regulator (LQR) controllers had better performance than Local Velocity Feedback (LVF) or Robust Eigensystems Assignment (REA) controllers. Since the LQR model-based controller provided the best performance, it is natural to select a model-based controller for high performance. However, model based controllers can lose stability margins due to model uncertainties. Thus, the approach taken by the Ground Test Methods team at Langley, is to concentrate first on a Low Authority Controller (LAC) loop using non-model based controllers for stability robustness. High Authority Controller (HAC) loops will then be closed to optimize the CEM LOS pointing. To this end, the following pages describe early non-model based controller results. In addition, finite element modeling and preliminary system ID test results are presented to indicate the level of model uncertainty to be expected during the design of high performance controllers.
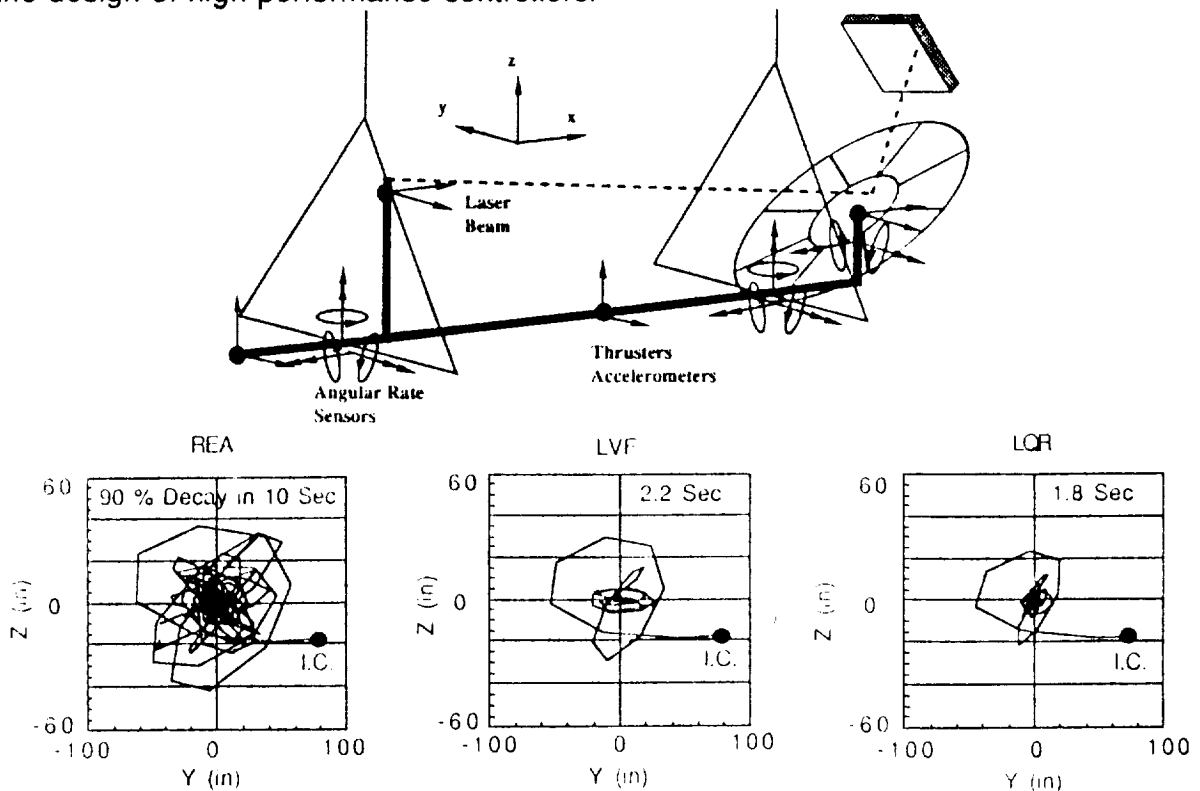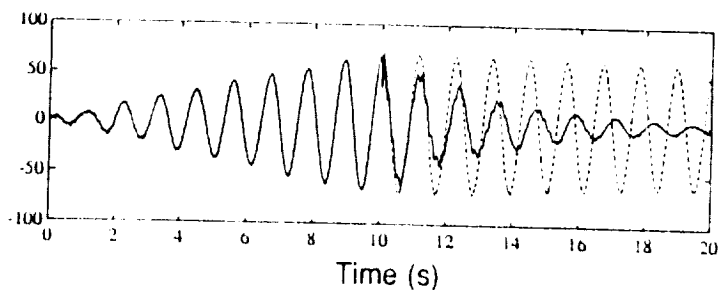
Virtual Passive Controller Results

A recent paper [4] documents a controller design approach based upon a virtual passive design philosophy. In effect, a spring-mass-damper system is designed using local sensor and actuator feedback to "absorb" the energy of the system. Although the resulting controller could be implemented with only passive elements, practical considerations usually lead to an active implementation. In the results below, 8 uncoupled second order systems were designed using collocated sensor/actuator feedback. The three traces show typical levels of damping produced by this controller. With the damping increased by factors of 3 to 8 over the open-loop damping using this highly stable LAC loop, high performance controllers are now practical. The model to be used for the HAC loop will be based upon a Finite Element Model (FEM) which is described next.

Mode 6 f=0.90 Hz
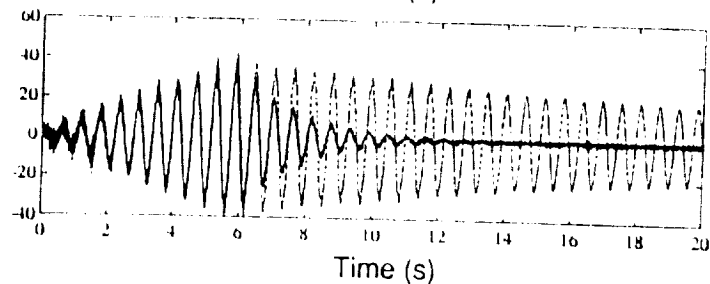$\zeta o = 0.60\%$ Acceleration
$\zeta c = 3.7\%$ (in/s^2)

Time (s)

Mode 8 f=1.71 Hz
$\zeta o = 0.66\%$ Acceleration
$\zeta c = 5.3\%$ (in/s^2)

Time (s)

Mode 9 f=1.90 Hz
$\zeta o = 0.49\%$ Acceleration
$\zeta c = 1.6\%$ (in/s^2)

Time (s)

10
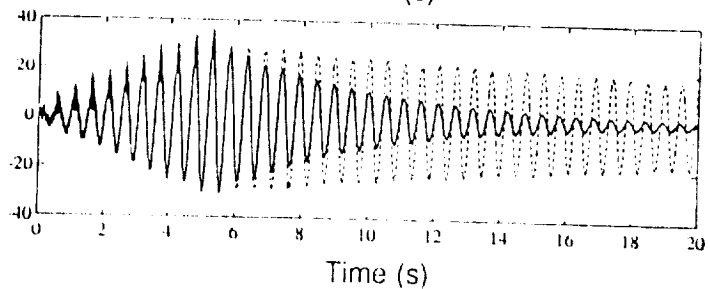
Finite Element Modeling of the CEM

The CEM was modeled with the NASTRAN program using beam, rod and plate elements. Since the CEM is cable suspended and gravity loaded, it was necessary to calculate the differential stiffness of the FEM elements to accurately predict the CEM dynamic behavior. The FEM, shown below without the truss diagonals for clarity, has all truss elements modeled from joint-to-joint with a single two-noded beam element. In addition, the reflector ribs and part of reflector to truss interface are modeled with beam elements. The mirrored panel and a portion of the reflector-to-truss interface was modeled with triangular plate elements.

The suspension cables were modeled by rod elements and spring elements. There exist over 3000 degrees of freedom in the model. A number of lumped masses representing the inertia of the node balls, actuators, sensors, etc. were included in the model. With the origin defined at the end opposite the reflector as indicated in the figure, the center of gravity is located at x=346.03 in., y=0.09 in. and z=19.85 in. The total mass of the model is 1.92319 lb-s^2/in. Rotational inertias in units of lb-in-s^2 are: Rxx=6915.94, Ryy=95197.13, Rzz=93558.3, Rxz=2288.47, Rxy=-17.74, Ryz=1.43.
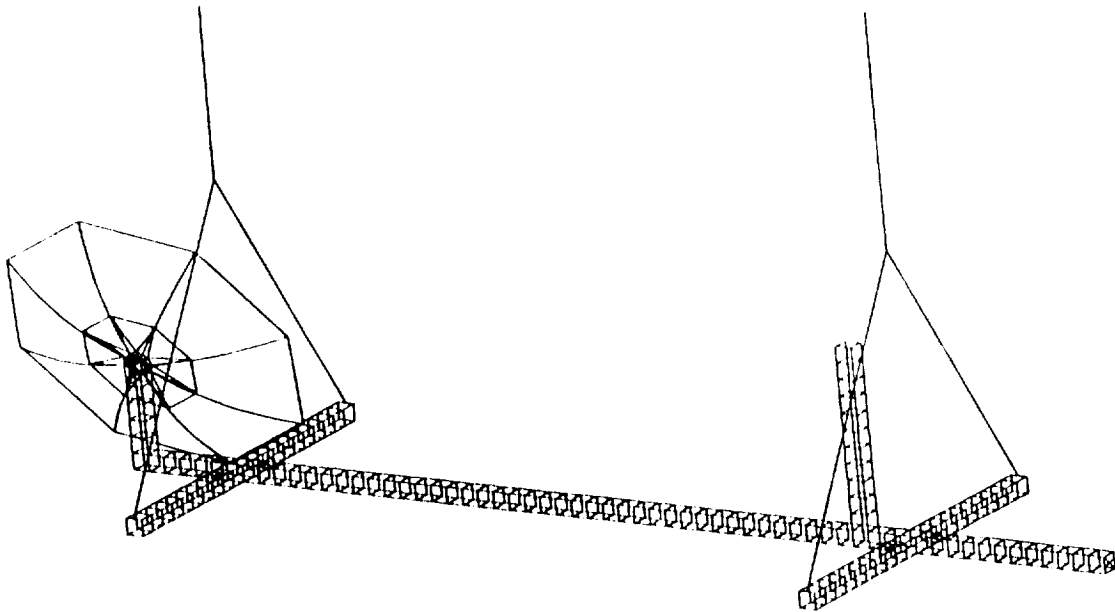
CEM Structural System ID Tests

Modal vibration tests of the CEM have been performed using 24 servo and 195 piezo channels of accelerometer data. Multi-Input, Multi-Output (MIMO) tests were performed to measure the frequency response functions (FRFs) between the acceleration output to force input. These FRFs are in process of being reduced to modal vibration parameters, namely frequencies, damping and mode shapes over the frequency range of 0 to 10 Hz. The plots below show typical FRFs taken in the vertical and horizontal planes at the center of the main truss. Also shown on the FRFs is the predicted response using the NASTRAN model. These data show relatively good agreement for some of the dominate modes, however, additional FEM refinement appears necessary. The next chart compares in more detail the system ID test and analysis results.
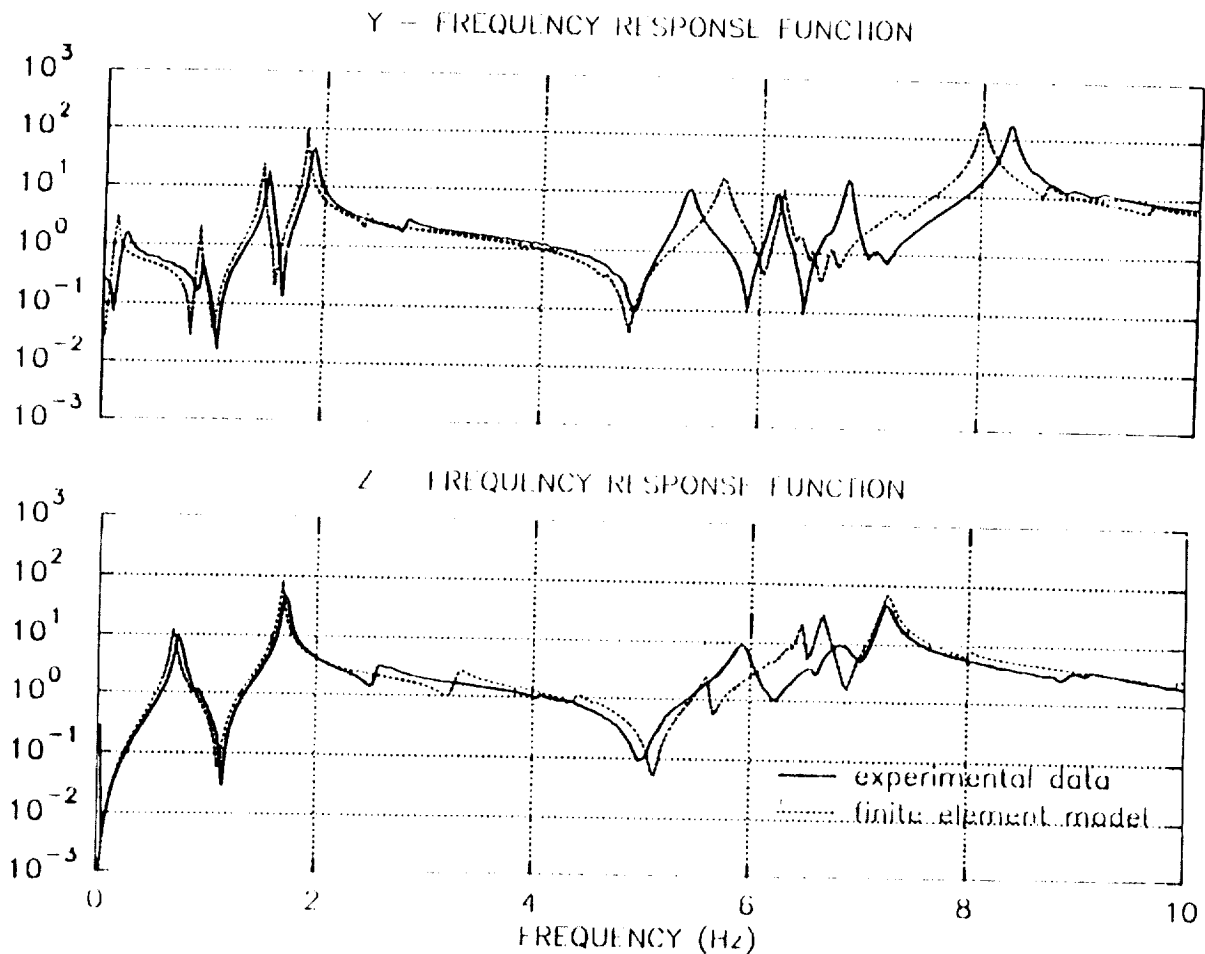
FREQUENCY (Hz)

System ID Test and Analysis Results

Preliminary results of the system ID testing described previously have been compared to the NASTRAN FEM in the table below. The data show the FEM model predicts the frequencies of the first three flexible body modes to an accuracy level of 5 percent or less. However, the first three "rigid" and several higher frequency modes are not predicted as well. Data reduction is continuing to identify all modes below 10 Hz. The open-loop damping data show the CEM to be lightly damped. This low inherent damping, typical of high quality truss structures, reinforces the need for augmenting the stability robustness by LAC loops. High modal density, low inherent damping and model uncertainty make the CEM an ideal testbed for development of CSI technology. The following pages describe plans for the CEM testbed research and development.

Mode Number	Test Damping %	Test Frequency	Analysis Frequency	Frequency Error %
1.	4.7	0.145	0.112	-22.8
2.	7.0	0.149	0.113	-24.2
3.	7.0	0.148	0.118	-20.7
4.	1.5	0.718	0.665	-7.4
5.	1.2	0.740	0.691	-7.1
6.	0.60	0.900	0.872	-3.1
7.	0.41	1.50	1.435	-4.3
8.	0.66	1.71	1.680	-1.8
9.	0.49	1.90	1.833	-3.5
10.			2.388	
11.			2.533	
12.	2.1	2.57	3.304	-22.2
13.			3.447	
14.			3.546	
15.			3.867	
16.	0.42	4.04	4.036	-0.01
17.	0.91	4.30	4.388	1.9
18.			4.574	
19.			4.648	
20.			5.599	
21.			5.609	
22.	0.69	5.33	5.648	6.0
	1.1	5.92		
23.	0.30	6.14	6.200	1.0
24.			6.351	
25.	0.30	6.65	6.473	-2.7
26.			6.660	
	0.22	6.79		
27.	0.56	7.24	7.253	0.2
28.	0.31	8.26	8.004	-3.1
29.	0.21	9.11	8.598	-5.6
30.			9.566	

Hardware Implementation of CSI Technology

The need for experimental verification of CSI technology is quickly realized when one tries to transform a paper design into hardware. "Real world" constraints such as using accelerometers because inertial displacement and velocity measurements are either unavailable or extremely expensive lead to controller modifications and sometimes new theoretical developments. The simplicity of SISO control, particularly for LAC loops using collocated sensors and actuators, leads to distributed rather than centralized processing and perhaps passive instead of active methods.

The Langley Ground Test Methods team seeks to develop a solid experience base for implementation of CSI designs in hardware. This experience base will be built by ground testing various actuators and sensors, implementing both localized and centralized controllers and developing ground test methodologies for verification of controlled structure designs. As indicated by the LAC/HAC schematic below, particular emphasis will be placed on the hardware implementation of LAC loops using analog, passive and local digital computing (e.g. DSPs) to enhance stability robustness for high performance controllers.
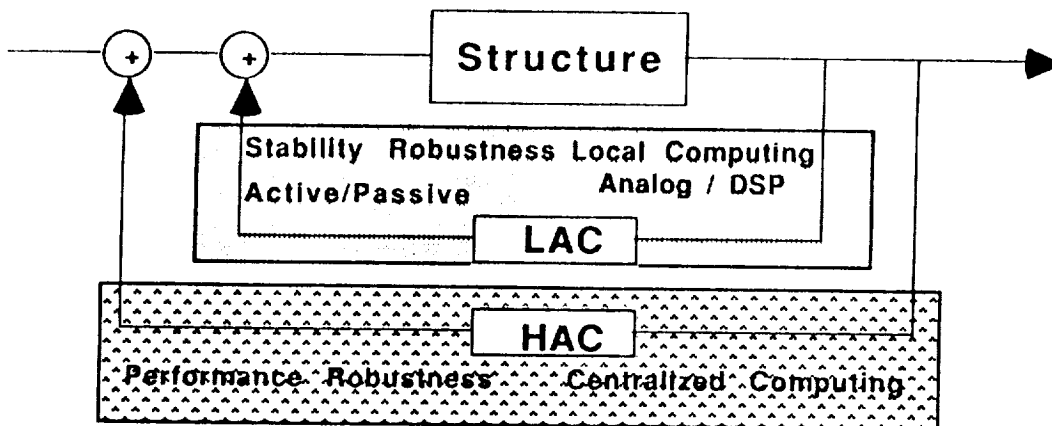
Integrated Controller Structure Design

The Phase-0 version of the CEM is constructed from uniform truss members which is typical of conventional spacecraft design. An exciting technology described in Ref. [5] and elsewhere is integrated structure and controller design. The Langley Analysis and Design Methods team is currently performing an integrated design for the CEM. The tailored truss resulting form this integrated design will be constructed and tested to assess the benefits of integrated structure and controller design. This new version of the CEM will be referred to as Phase-1.

$$\text{Optimal Structure} + \text{Optimal Controller} \neq \text{Optimal System}$$

- -

$$\text{Simultaneous Design of Structure and Controller} = \begin{array}{l}\text{Better Performance}\\ \text{Less Control Energy}\\ \text{Lower System Weight}\end{array}$$

Planned Evolution of the CEM

The CEM will evolve from Phase-0 to Phase-1 in calendar year 1991 as indicated below. Phase-1 tests will verify the integrated design approach and will use the best implementation of hardware based on Phase-0 testing. Methodologies for on-line verification of stability and robustness will be studied to verify the design. Global LOS pointing will remain the primary performance criteria.

In calendar year 1992, the Phase-1 hardware will be modified by included gimbaled appendages. This new configuration, referred to as Phase-2 will continue to build upon Phase-0 and Phase-1 experience, however, the focus will be on multi-payload isolation. In addition, numerous advances in hardware and theory will be needed to design and simulate the time varying robotic nature of Phase-2.

CY-90   CY-91   CY-92   CY-93

Phase-0
Uniform
Truss

Phase-1
Integrated
Structure and Control
Design

Phase-2
Multi-Payload
Gimbaled
Appendages

Summary

The Phase-0 version of the CEM is operational and preliminary control and system ID results have been presented. Non-model based controllers using collocated sensors and actuators provide an order of magnitude increase in the open-loop damping and should enable good stability robustness for high performance controllers. Model based control design will not require extreme conservatism on model uncertainty since the system ID data and the FEM data show reasonable agreement. Of course, model based controllers will be affected by unmodeled dynamics and perhaps spillover since the CEM has high modal density.

Hardware implementation issues of controlled structure systems are being studied to enhance simplicity, cost-effectiveness and reliability using the CEM testbed. Actuator/sensor tests, active/passive implementations and centralized/distributed computing are being performed to build an experience base for future CSI systems. This experience base will be mandatory for developing verification methodologies of CSI designs.

The planned evolution of the CEM will provide a ground based testbed to develop focused CSI technology for both linear time invariant systems as well as multi-body dynamic systems. Periodic reporting of CEM test results will continue in this forum.

Acknowledgements

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